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High duty cycle germanium lasers and continuous terahertz emission from germanium

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Abstract – **We have measured laser emission from beryllium-doped germanium crystals with small inter-contact distances. An improved heat sink allowed a two-fold increase of the laser duty cycle to 5%. Non-thermal terahertz emission was found for conventional, continuously excited beryllium-doped germanium crystals with a volume of 0.5 mm³. Experimental and theoretical investigations of germanium lasers headed for continuous wave operation will be discussed. Major emphasis is placed on the electric field uniformity. We present experimental results of lasers utilizing a planar contact geometry. A planar laser structure with a thin active layer seems to be a very good candidate for a high power and continuous wave terahertz laser.**

I. INTRODUCTION

The germanium laser has become an interesting candidate for far-infrared and time-resolved spectroscopy due to the recent improvement of germanium laser material [1,2] combined with technological advances in the laser operation, e.g., using permanent magnets in a closed cycle refrigerator [3,4,5] and mode-locking [6,7].

Germanium lasers provide high power emission which is widely tunable from 1 to 4 THz [8] with narrow line widths below 1 MHz [9]. Linear polarization is achieved in the Voigt configuration [4]. The pulse length can be several tens of picoseconds [6,7] to several tens of microseconds [10].

The pulsed output power can reach 5-10 W [11,12]. An even higher peak power can be expected with mode-locking and cavity dumping. Laser emission is normally observed at temperatures from 4 to 40 K [10] but higher temperatures (65 K and 80 K) were also reported [13].

We have also demonstrated pulsed laser emission from smaller crystals that only consume 4 W of electrical power [10].

In the continuous wave mode an output power of several tens of μW to tens of mW can be expected. The theoretical conversion efficiency of 0.5% [14] can lead to a generated output power of 5 mW at an electrical pump power of 1 W. Modern closed cycle refrigerators easily cool a heat load of 1 W to 4.2 K.

II. HIGH DUTY CYLE AND CONTINUOUS EXCITATION OF GERMANIUM CRYSTALS

Previously, we have used oxygen free high conductivity copper with a purity of 99.95% as a heat sink for our

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lasers [10]. The heat sinks were attached to the ohmic contacts of the lasers. However, the heat conductivity of this copper material is lower than that of germanium laser material below 20 K (see Table 1, germanium values for an acceptor concentration of $N_A = 10^{14}$ cm⁻³).

Table 1: Heat conductivity of different materials at low temperatures.

T [K]	99.999% Cu [Wcm⁻¹K⁻¹]	99.95% Cu [Wcm⁻¹K⁻¹]	Ge [Wcm⁻¹K⁻¹]	In [Wcm⁻¹K⁻¹]	He [Wcm⁻¹K⁻¹]
4	70	3.2	8	8	2.6E-4
10	135	8	18	4	1.7E-4
20	90	13	15	2	2.6E-4
30	40	14	10.5	1.2	3.4E-4

We have therefore replaced these heat sinks with high-purity copper material with a purity of 99.999%. Thin indium layers were also omitted in contrast to previous studies [1,3].

Because of these new heat sinks the duty cycle of a larger laser of 162 mm³ volume was doubled and the time-averaged input power was raised from 8 to 17 W [13].
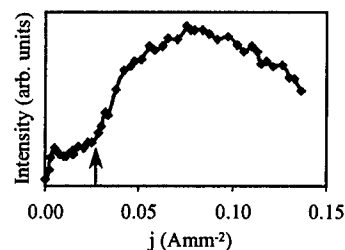

Fig. 1: Laser emission of a Ge:Be laser vs the current density *j* at a duty cycle of 5%. The arrow indicates the laser threshold.

Using the high-purity copper heat sinks we have studied Ge:Be lasers with small inter-contact distances. Figure 1 shows the laser emission of a crystal of 20 mm³ volume with a contact distance of 0.8 mm. The ohmic contacts of 24.5 mm² area allowed sufficient cooling. The laser threshold current was 600 mA, and the threshold voltage was 31 V. Hence, the input power during the pulse was 19 W. The latter corresponds to an average input power of 0.95 W for the duty cycle of 5%. The two-fold increased repetition rate of 5% (previously 2.5% in ref. [10]) was only limited by the available pulse generator.

Non-thermal emission has also been found for small *continuously* excited Ge:Be crystals with a volume of 0.5

mm³ (Fig. 2) [15]. These devices only need 1 to 4 W electrical input power .
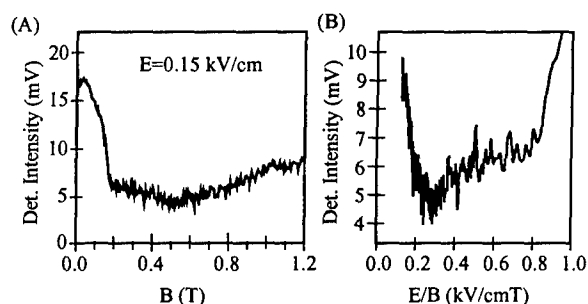
(A)

E=0.15 kV/cm

(B)

Fig. 2: *Continuously* excited Ge:Be laser material at E = 0.15 kV/cm (A) vs the magnetic field and (B) vs the E/B-ratio. Emission above 0.5 T could be related to cyclotron resonance emission of light holes. Emission from intervalence band transitions is expected below 0.2 T.

Recently, we obtained a modern closed cycle refrigerator (SRDK-408D made by Sumitomo Heavy Industries, Ltd., Japan) and measured a temperature of 4.2 K and 20 K at heat loads of 1 W and 42 W, respectively. Future experiments will use this machine to deliver the required continuous cooling power for a continuous wave laser.

III. ELECTRIC FIELD UNIFORMITY

The formation of a population inversion in the germanium crystal requires uniform magnetic and electric fields which have to be perpendicular to each other. However, the electric field distribution of common lasers is very non-uniform due to the Hall electric field. This non-uniformity largely depends on the chosen crystal dimensions and the geometry of the ohmic contacts.

Advanced germanium laser material [2] allows a variety of laser shapes [16]. Subsequently, there are multiple possibilities to dramatically improve the field uniformity and enhance the laser conversion efficiency.
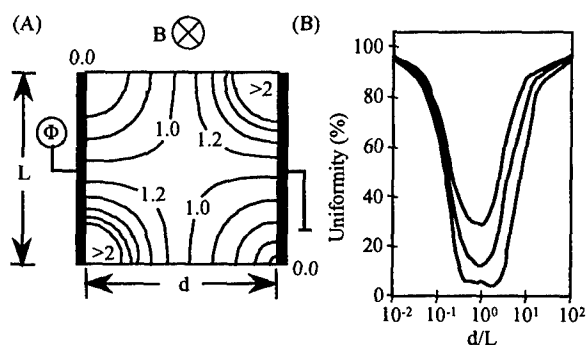
(A)

(B)

Fig. 3: (A) Electric field distribution in a laser crystal with a square cross-section in kV/cm for an applied field of 1 kV/cm. (B) Calculation of the electric field uniformity as a percentage of the crystal volume. The set of three lines corresponds to an electric field deviation $\Delta E_T/E_T$ of 1%, 10%, and 40%.

The field uniformity is very important because the lifetime of the carriers in the upper laser states strongly depends, *i.e.*, by many orders of magnitude for deviations of only 1%, on the electric field strength.

This lifetime also strongly depends on the field orientation with respect to the crystallographic axes. This orientation varies across the laser cross-section but will not be discussed here.

Figure 3A shows a calculation of the electric field distribution perpendicular to the magnetic induction B in a laser crystal with a square cross-section. Commonly used germanium lasers have a cross-section which is very close to a square cross-section.

Figure 3B displays a calculation of the electric field uniformity as a percentage of the crystal volume and a function of the cross-section dimension ratio d/L. The set of three lines corresponds to an electric field deviation $\Delta E_T/E_T$ of 1%, 10%, and 40% with respect to the total electric field E_T in the crystal center. For example, the electric field deviates by more than 1% from the center field in 94% of the crystal volume for a d/L-ratio of 0.5, which has been used for high duty cycle lasers (dc = 2.5%).

A high d/L-ratio and therefore a high uniformity (Fig. 3B) can be obtained by using a planar device structure [16,17]. In this case the electric field is uniform between the contacts.
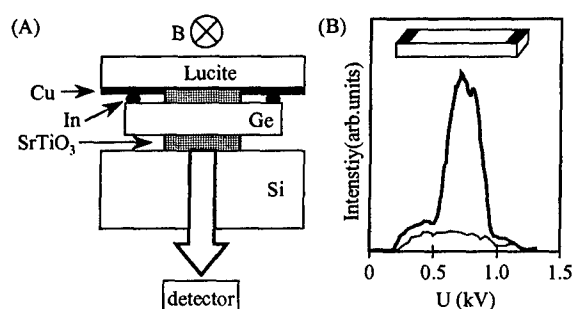
(A)

(B)

Fig. 4: (A) Planar germanium laser using SrTiO₃ mirrors. The coplanar ohmic contacts (see inset in Fig. 4B) are connected via indium (In) to copper foils glued to Lucite. A Ge:Al photoconductor detects the laser emission through the silicon heat sink. (B) Emission of a Ge:Be planar laser as a function of the applied voltage with (upper, thick line) and without (lower, thin line) SrTiO₃ mirrors.

Figure 4 shows a planar germanium laser with two dielectric mirrors made from SrTiO₃. This material has a high reflectivity in the far infrared due to reststrahlen bands. Dielectric materials are also advantageous because they do not disturb the electric field distribution in contrast to commonly used metal mirrors. The sample thickness between the mirrors was only 2.2 mm, and the contact distance was 10 mm (d/L = 4).

Beryllium-doped germanium seems to be the laser material of choice which allows one to construct relatively arbitrary shapes because the generated photons are not absorbed by impurity related transitions. Unexcited germanium material within the laser sample is transparent in the far infrared and it can act as a heat sink.
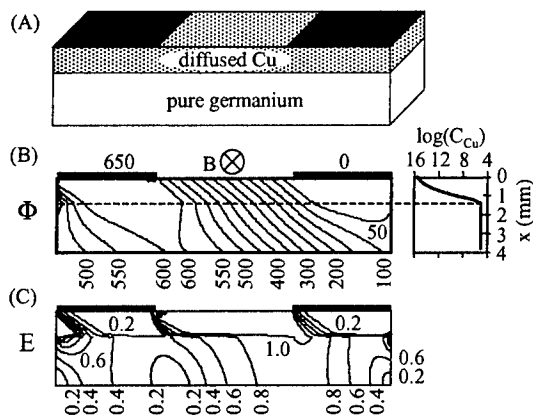
Fig. 5: (A) Potential continuous wave laser with coplanar ohmic contacts. A thin active layer is formed by copper diffusion. (B) Calculation of the potential lines (Φ) perpendicular to a magnetic induction B for a calculated copper diffusion profile of concentration C_{Cu}. The potentials on the two contacts are 0 and 650 V. (C) Electric field distribution in 0.2 kV/cm intervals for a contact spacing of 10 mm.

A laser consisting of a thin active, doped layer introduced by diffusion in a larger pure germanium substrate seems to be an ideal candidate for a continuous wave terahertz laser.

Copper is easily diffused in germanium in a relatively short time. A 1 mm thick, active layer is fabricated within a few hours (Fig. 5). In this device structure we can naturally obtain a very large d/L-ratio (in Fig. 5, $d/L = 10$) and find a uniform electric field region between the ohmic contacts (Fig. 5C). Beryllium diffuses much slower than copper in germanium. Therefore, very thin active layers can be fabricated, e.g., a 25 µm active layer is formed within 3 days at 800°C.

IV. CONCLUSION

Although the germanium laser material was optimized for bulk germanium crystals [2] little work has been done to optimize the laser device with respect to geometry.

Especially, the high non-uniformity was not considered to be crucial. We have shown that remarkable field improvements can result if planar lasers are used. They can dramatically improve the power conversion efficiency.

Dielectric materials can serve as mirrors in planar laser structures. They do not disturb the electric field distribution in contrast to commonly used metal mirrors. Nevertheless, laser emission at high duty cycles and non-thermal emission at continuous excitation were observed for non-optimized lasers using d/L-ratios close to unity.

A thin active layer within a pure germanium substrate seems to be a good candidate for a high power and continuous wave terahertz laser. A large d/L-ratio is naturally obtained. The high-purity and undoped germanium substrate can act as an efficient heat sink and heat conductor without a thermal interface to the active layer.

Future applications of germanium lasers in far-infrared spectroscopy of chemical and biological species [18] will certainly show the uniqueness and the value of this tunable semiconductor laser source in the far infrared.

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